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NAS8-9049
DRA

Management
Summary
Presentation

April 1978

Reduction of Liquid Hydrogen Boiloff: Optimal Reliquefaction System Design and Cost Study

Publication of this document does not constitute National Aeronautics and Space Administration endorsement of the findings or conclusion of the report.

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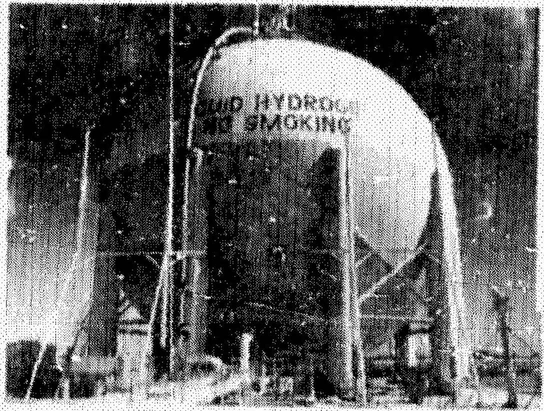
POTENTIALLY RECOVERABLE LH_2 LOSSES

Daily H_2 Boiloff:	400 Gal
H_2 Loss-Blowdown After Loading	14,400 Gal
H_2 Loss-Blowdown After Launch	14,000 Gal



Shuttle H_2 Storage
850,000 Gal. Dewar at LC-39A & 39B

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Recognizing that hydrogen losses in excess of 220,000 pounds at a cost of approximately $385,000 for each Space Shuttle launch facility will occur for each year of operation, the NASA Kennedy Space Center sponsored a study to determine the technical and economic feasibility of recovering the hydrogen boiloff gases. This presentation highlights the results of that study, performed by the Martin Marietta Corporation, Denver Division.

The study encompassed two contracts. The first, NAS10-8937, concentrated on thermal analyses of competitive refrigeration cycles, developed preliminary conceptual designs of LH_2 reliquefaction systems and computer models for cycle performance and life cycle cost analysis. The second, NAS10-9049, concentrated on the most promising system (a closed loop LN_2 precooled refrigeration cycle) and developed a detailed system design concept, conducted additional performance analysis to establish optimum performance parameters and size the system components, developed a system controls concept, performed safety analyses, defined the required facility modifications, produced a plan for implementation, reiterated the life cycle cost analyses, and performed a detailed analysis of the required capital investment costs.

SCOPE OF LH_2 RELIQUEFACTION STUDY

	NAS 10-8937	NAS 10-9049
Preliminary Analysis of Thermodynamic Cycles	XXXXX	
Conceptual System Design	XXXXX	XXXXX
System Cycle Performance Analysis	XXXXX	XXXXX
System Controls Concept		XXXXX
Failure Modes and Safety Analysis		XXXXX
Facility Modification Concept		XXXXX
Implementation Plan		XXXXX
Life Cycle Cost Analysis	XXXXX	XXXXX
Capital Investment Cost Analysis		XXXXX

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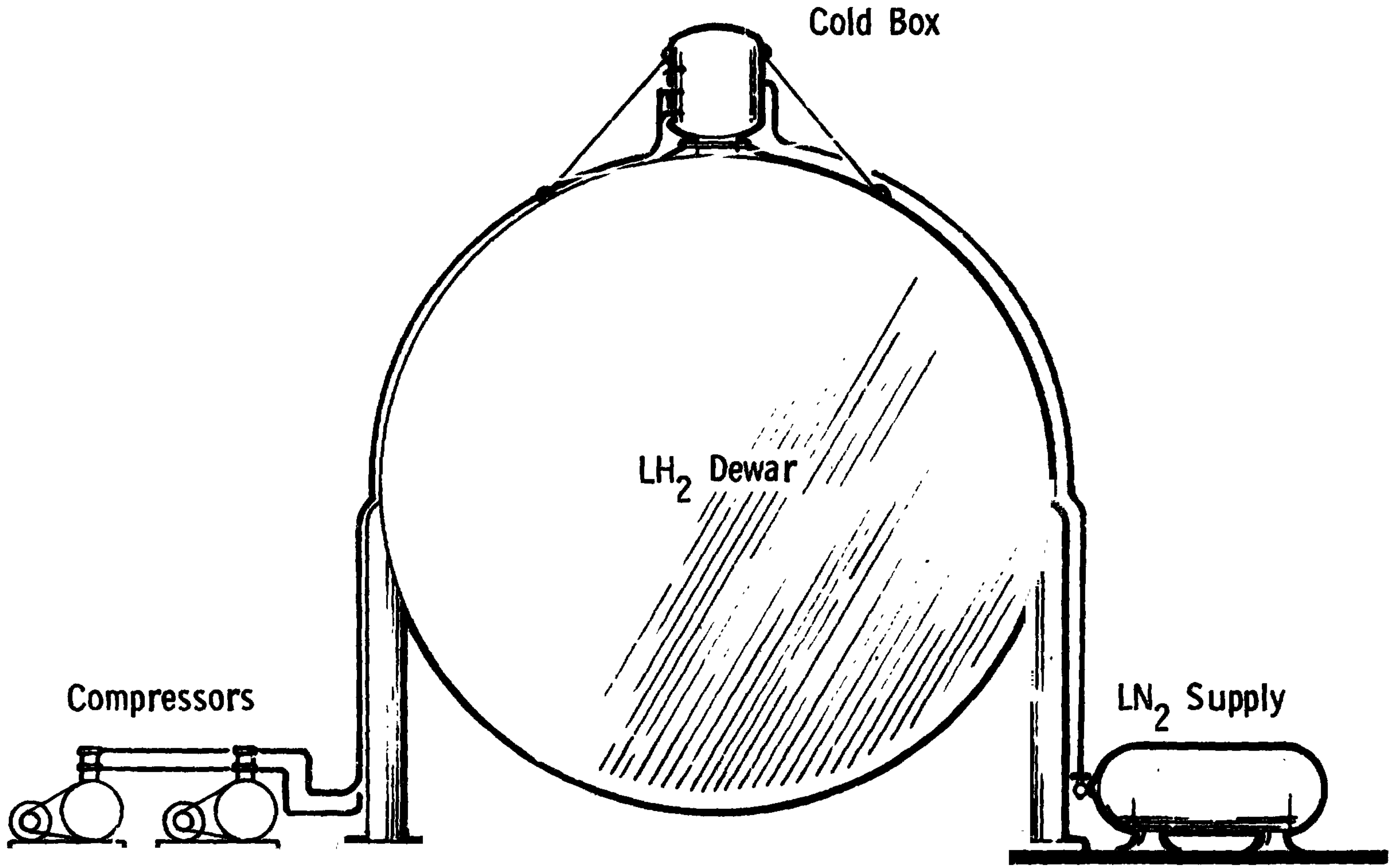
The hydrogen reliquefaction system is made up of four major components consisting of the existing LH_2 storage dewar, the cold box (hydrogen refrigeration unit) mounted on top of the dewar, two hydrogen compressors, and a LN_2 supply system. The technology for producing each of these items currently exists, as there are several reliquefaction systems operational today. The unique features for the Space Shuttle system are the system size and the operational environments.

HYDROGEN RELIQUEFACTION SYSTEM MAJOR COMPONENTS



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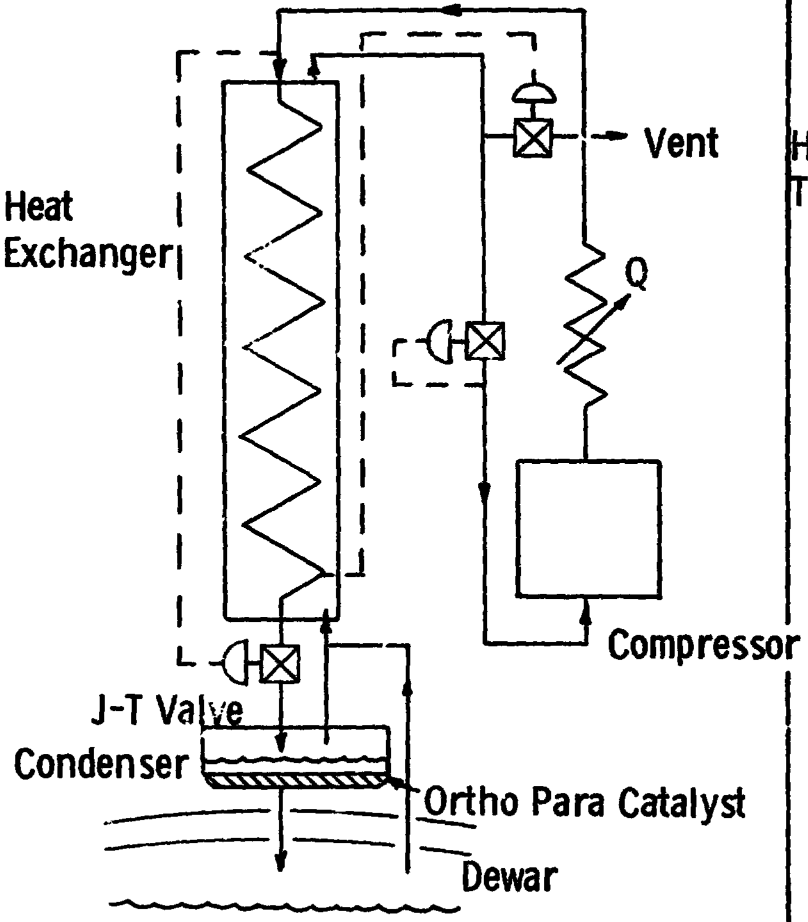
The refrigeration cycles investigated are referred to as Joule-Thomson cycles because they depend on the J-T effect to produce the low temperatures. Two basic competitive refrigeration cycles were evaluated. The first vents a portion of cold H_2 gas to achieve the required precooling; the second uses LN_2 for precooling. Both open loop and closed loop cycles were evaluated as well as combinations of venting to supplement the LN_2 precooling.

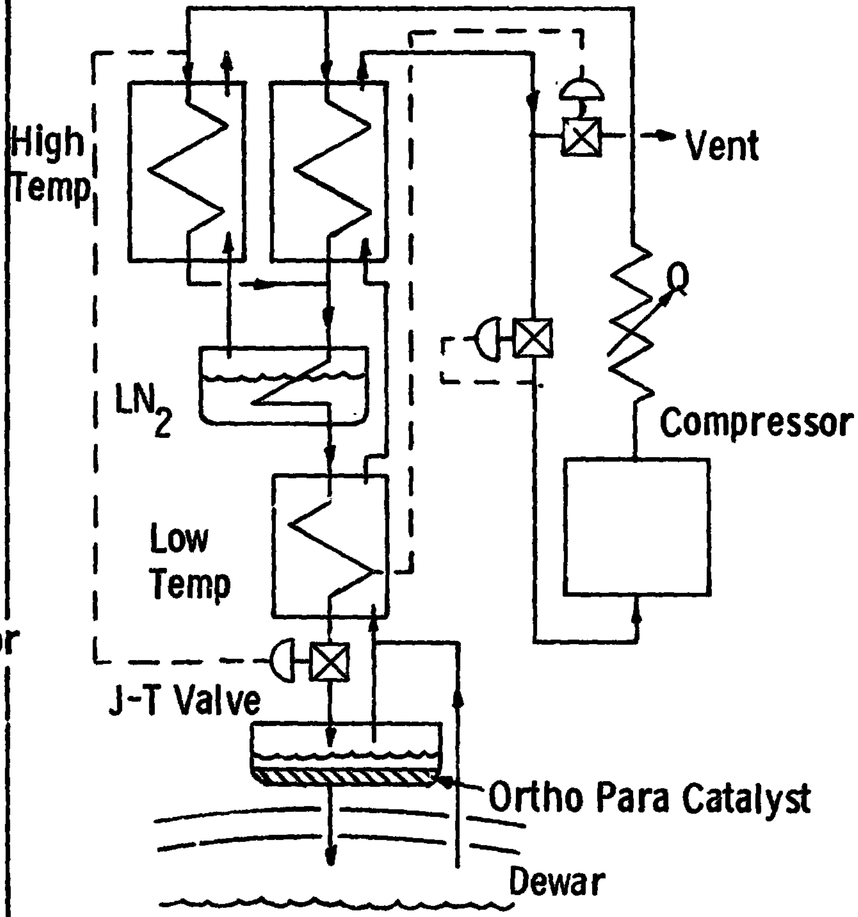
All cycles use a H_2 compressor to achieve the desired high pressure (1325 psig). The heat of compression is removed by cooling water. The high pressure H_2 gas is cooled in counterflow heat exchangers by flowing cold H_2 to the compressor. Further cooling is achieved for cycles using LN_2 by passing H_2 vapors through a LN_2 heat exchanger. Finally, the high pressure H_2 gas is expanded through a J-T valve where a portion of the H_2 is liquefied. The low pressure H_2 gas flow back through the heat exchangers to the compressor is that portion not liquefied and make up hydrogen gas from the dewar. For the vent cycle an additional amount of H_2 gas from the dewar is vented through the heat exchanger to give the required precooling.

The advantage of the vent cycle is its simplicity resulting from only one heat exchanger. The disadvantage is its comparatively poor performance due to the losses of the vented H_2 gas. The size of the two systems is about the same.

OPEN LOOP REFRIGERATION CYCLES



Vent Cooling Reliquefaction Cycle



LN_2 Precooled Reliquefaction Cycle

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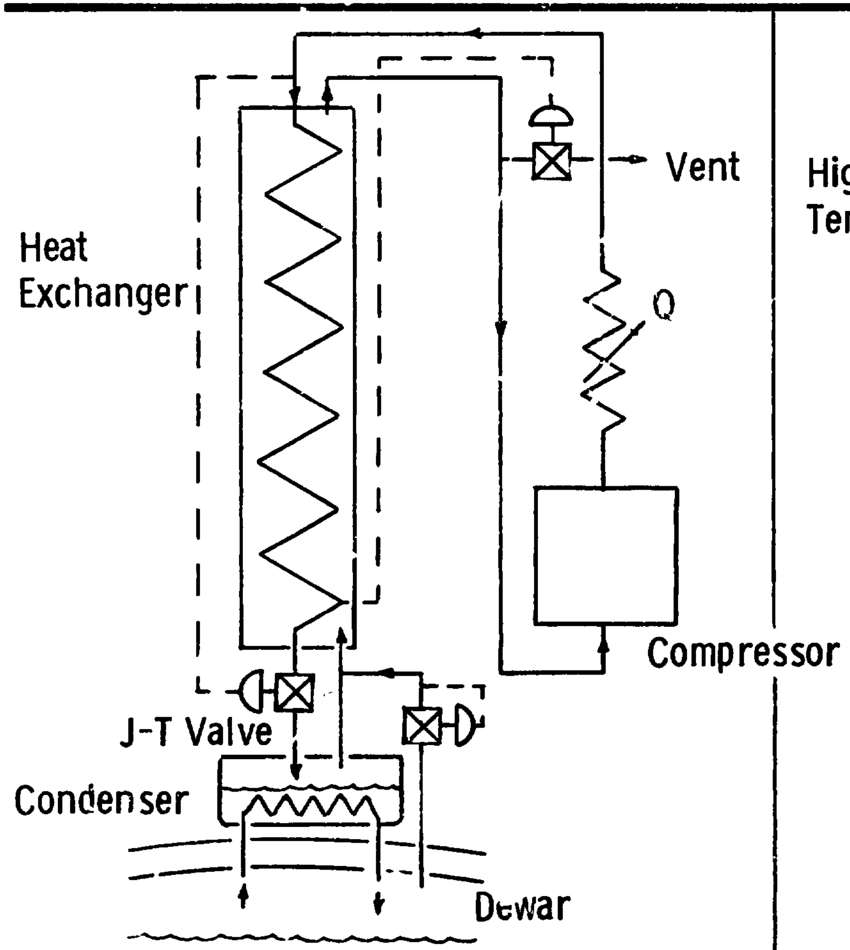
Two alternatives to the basic cycle were evaluated:

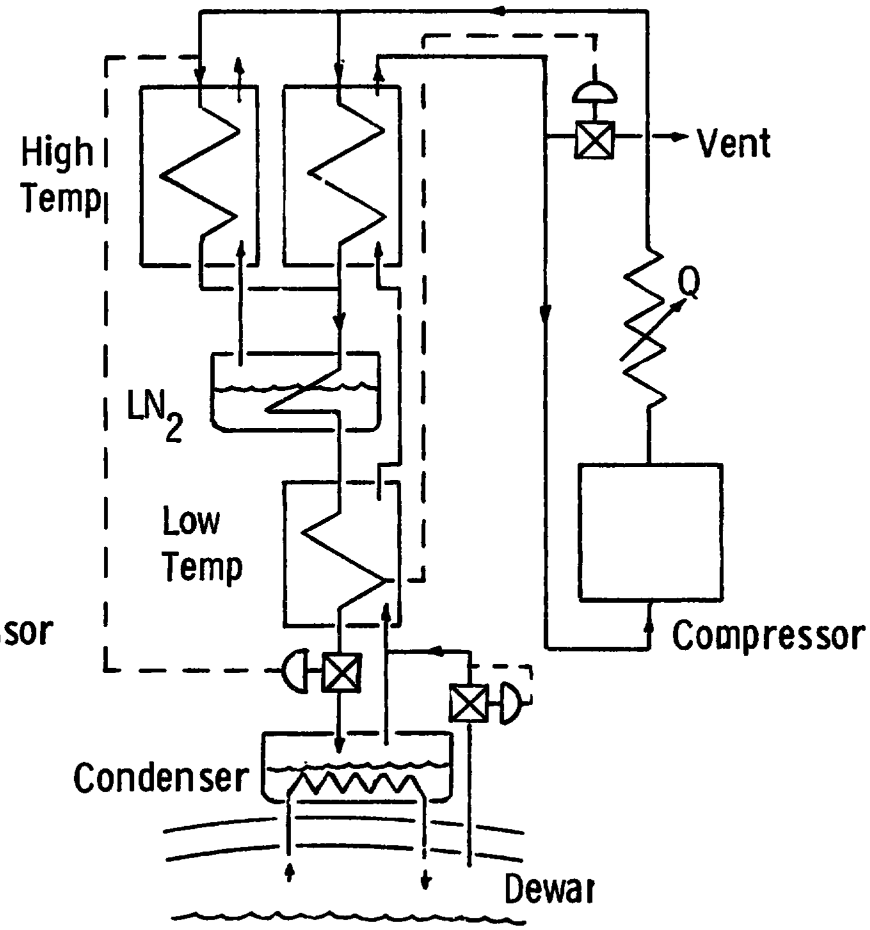
- The one just discussed assumed an open loop in which the H_2 circulated through the cycle is reintroduced into the dewar.
- The other assumed a closed loop system that does not reintroduce the circulated H_2 into the dewar.

The LN_2 precooled cycle has considerable economic advantage because excessive quantities of H_2 are not lost through venting. The closed loop cycle has operational and safety advantages because the circulated H_2 is not reintroduced into the system. For these reasons the closed loop LN_2 precooled cycle was selected for further development under the initial contract.

CLOSED LOOP REFRIGERATION CYCLES



Vent Cooling Reliquefaction Cycle



LN_2 Precooled Reliquefaction Cycle

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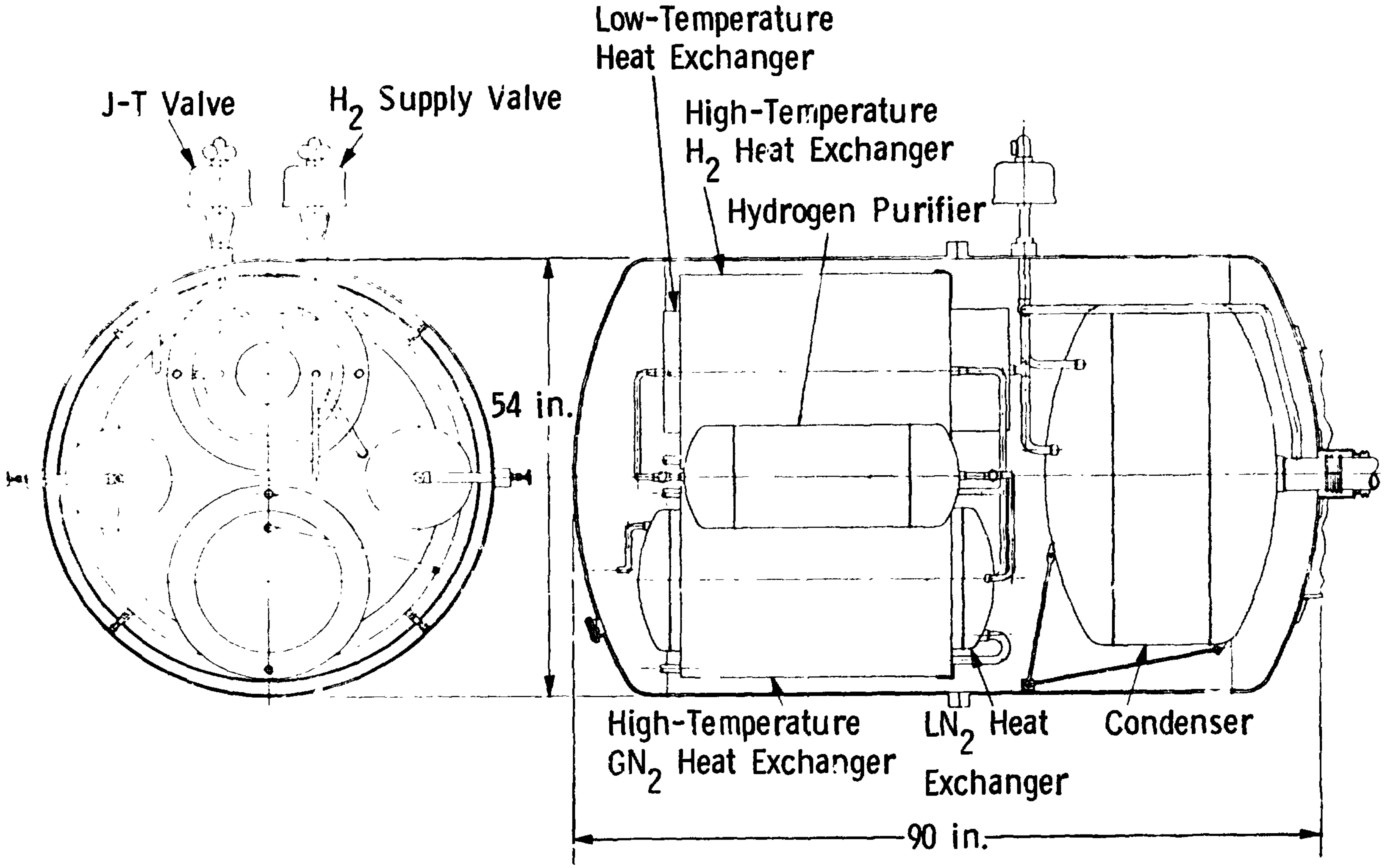
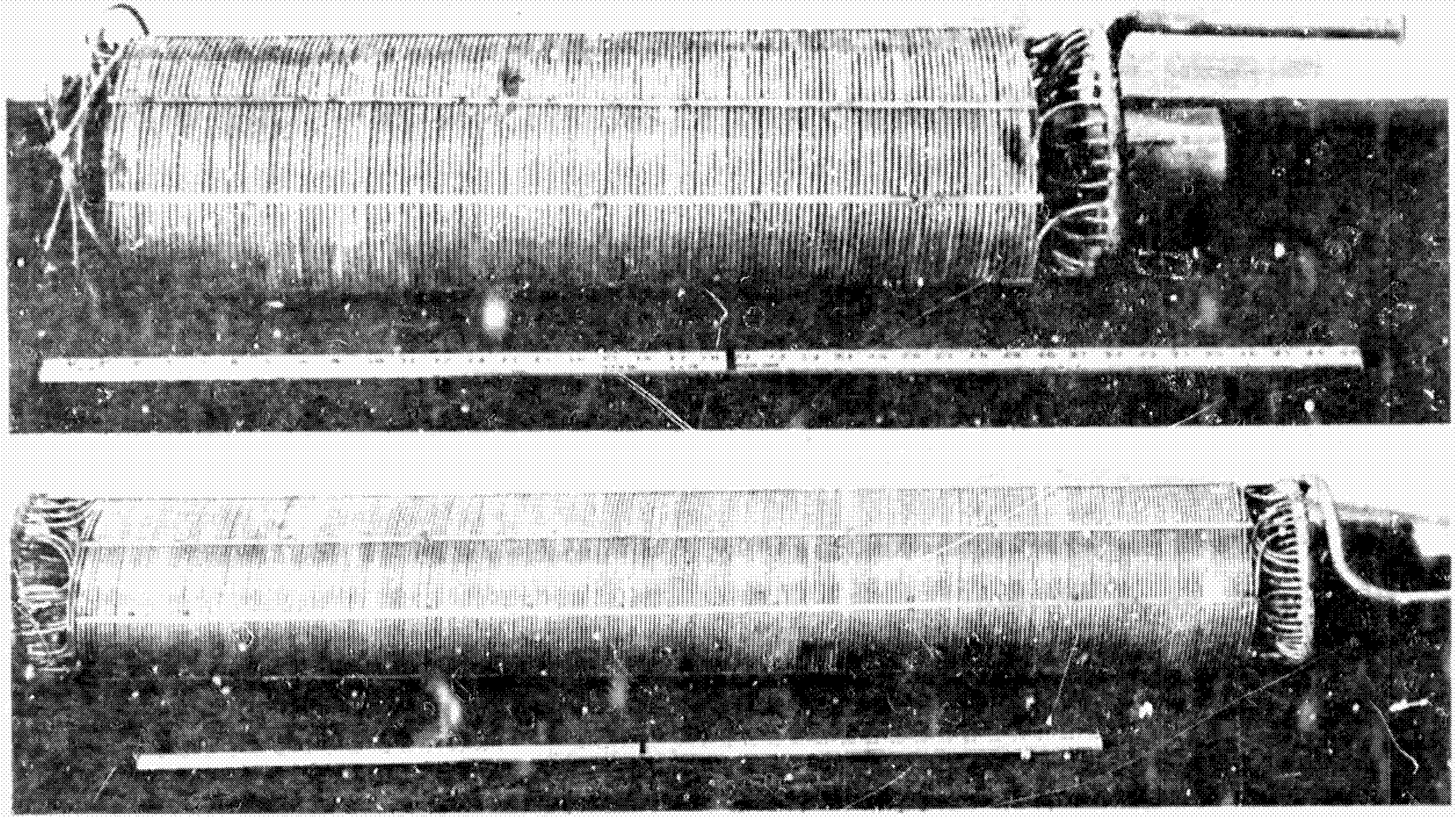
The various heat exchangers and condenser were sized by the thermodynamic computer program, i.e., the tube size, area, number of turns, etc. Detail layouts of each item were then developed to define component size and weight. These items were then packaged into a cylindrical closure 54 inches in diameter and 90 inches long. The cold box is vacuum insulated and filled with perlite. It is a seal welded stainless steel enclosure. No access is required into the cold box for maintenance. The valve bonnets protrude through the enclosure to permit valve maintenance, if required.


Low-Temperature
Heat Exchanger
J-T Valve
H_2 Supply Valve
High-Temperature
H_2 Heat Exchanger
Hydrogen Purifier
54 in.
High-Temperature
GN_2 Heat Exchanger
LN_2 Heat
Exchanger
Condenser
90 in.

Shown in the photographs are typical heat exchangers of the type used in the cold box. These heat exchangers are precision wound by special equipment developed by Cryenco of Denver, Colorado, and were used in an application similar to the LH_2 reliquefaction system.

TYPICAL HEAT EXCHANGERS



Courtesy of Cryenco

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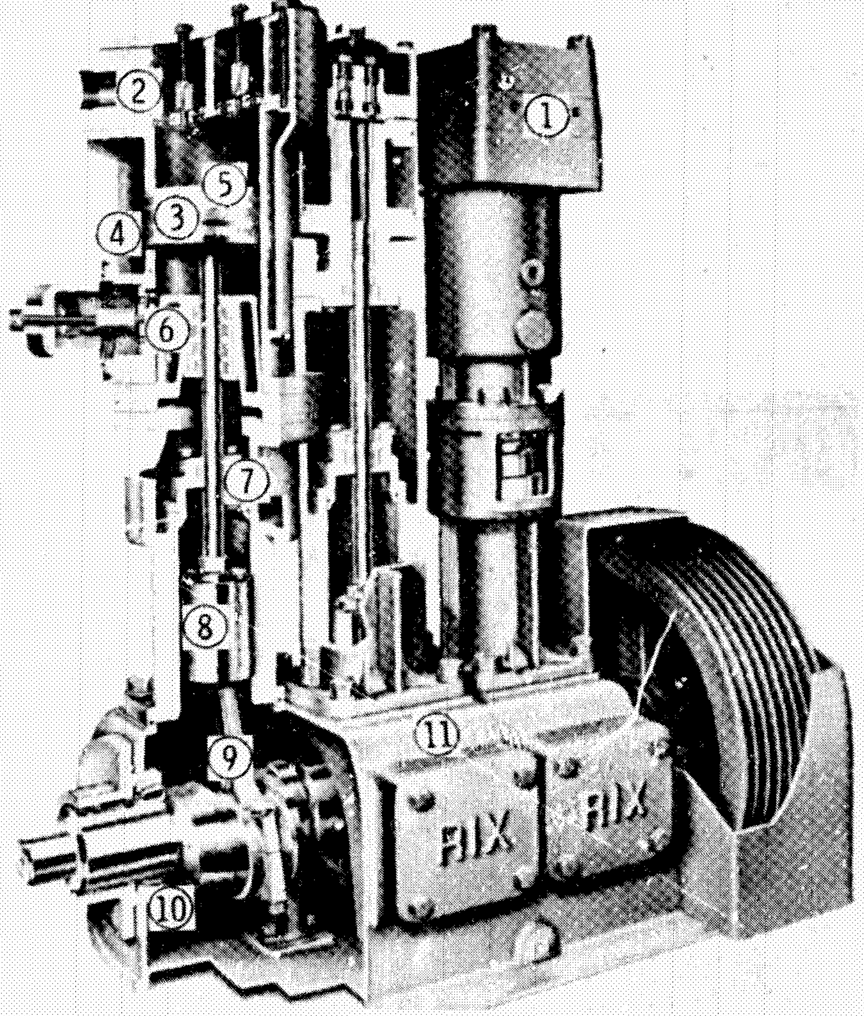
The system requires the use of two industrial compressors similar to the one illustrated. These compressors are built up from standard components with capacities from 3 to 500 horsepower at pressures up to 10,000 psi. The LH_2 liquefaction system requires a 75-HP unit with an exit pressure of 1325 ps , and a suction pressure as low as 10 psia. Gaseous hydrogen flow is 106 SCFM for normal daily operation and doubles when the second compressor is brought on line for the recovery period following dewar loading or Shuttle loading. The compressor power consumption is 42 KW for the single unit and doubles during the dewar recovery operations.

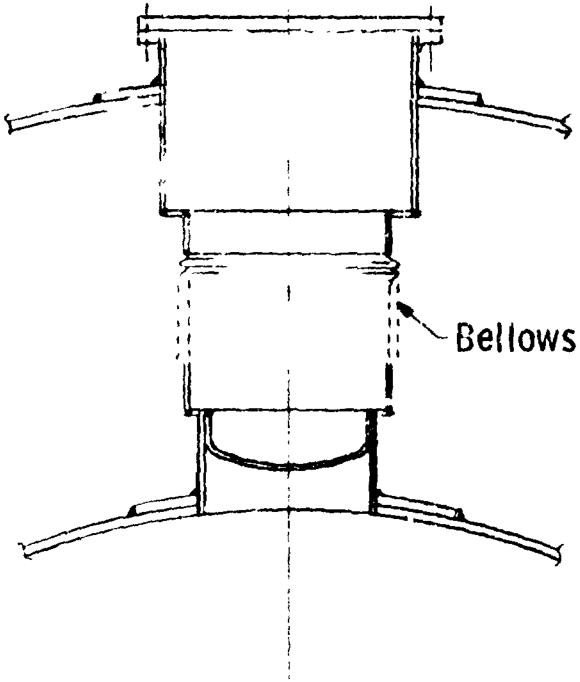
This unit features compression cylinders completely isolated from the oil lubricated crank-case by crosshead distance piece and specially designed gas seals. Vertical reciprocating pistons eliminate egg-shape cylinder wear common to horizontal designs. Six thousand hours operation may be anticipated between overhauls; two thousand hours between overhauls, however, was assumed in the life cycle cost analysis.

COMPRESSOR FEATURES

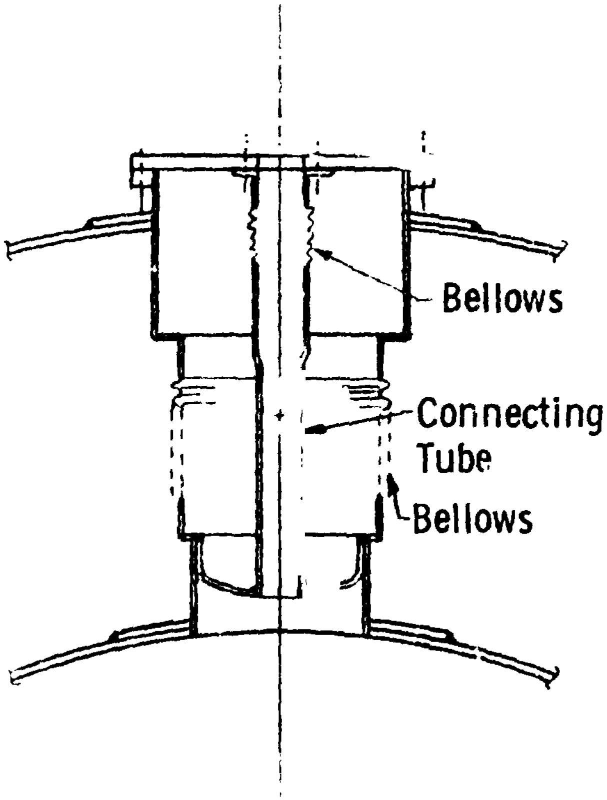
1 Cylinder Heads
2 Valves
3 Piston Rings
4 Water Jackets
5 Pistons
6 Gas Seals
7 Oil Seals
8 Crosshead
9 Connecting Rods
10 Main Bearings
11 Crankshaft



Th LH_2 reliquefaction system must penetrate the existing LH_2 dewar. The condenser may be located either in the ullage of the LH_2 dewar or in the cold box. It is recommended that the condenser be placed in the cold box to simplify the dewar/reliquefaction system interface. It is essential that the penetration does not contaminate or degrade the structural and vacuum capability of the dewar. This may be accomplished by making the penetration through the existing manhole cover and dish-shaped closure for the inner vessel. The connecting tube is welded to the dish-shaped closure and has double teflon seals at the manhole cover. Expansion bellows in the connecting tube provide the required relative movement between the inner and the outer tank shells.



Existing Manhole



Manhole Modification

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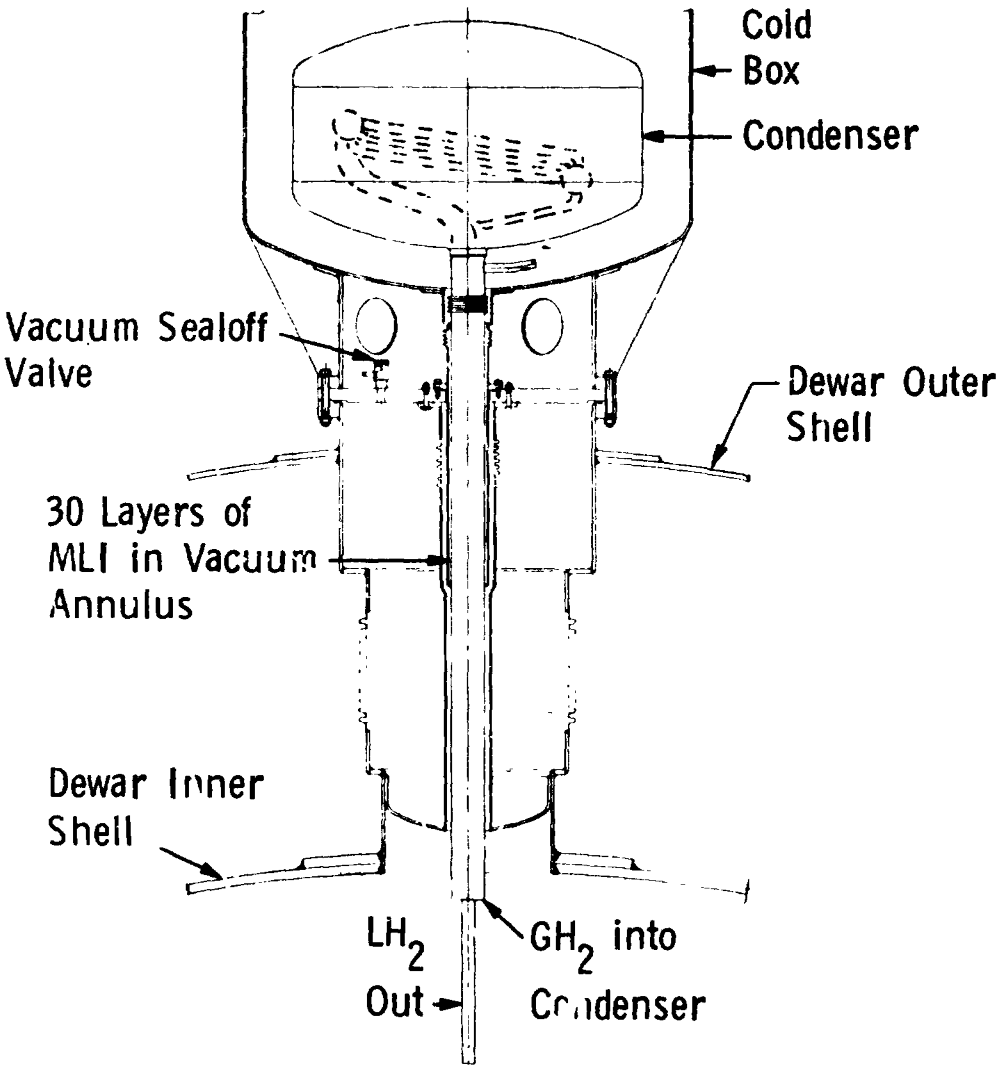
The gaseous hydrogen inlet to the condenser and the condensed hydrogen exit from the condenser back to the dewar are concentric tubes that extend from the cold box into the ullage of the dewar. The gaseous hydrogen inlet is vacuum insulated with vacuum common to the cold box. This design approaches a zero thermal loss, due to the penetration.

The gaseous hydrogen from the dewar ullage circulates through the condenser, is liquefied and returns to the dewar. It is not exposed to the refrigeration cycle gas.


Cold
Box
Condenser
Vacuum Sealoff
Valve
Dewar Outer
Shell
30 Layers of
MLI in Vacuum
Annulus
Dewar Inner
Shell
LH_2
Out
GH_2 into
Condenser

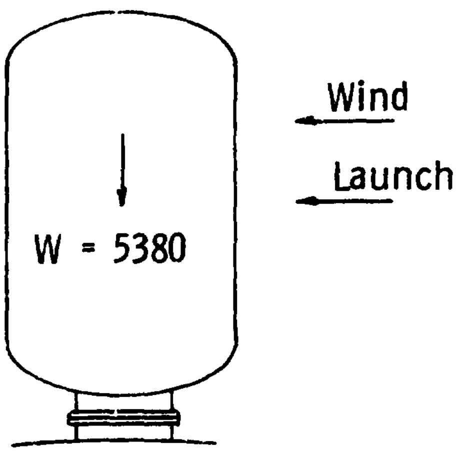
The cold box introduces a dead load of 5380 lb into the outer dewar shell due to its weight and a moment into the manhole mounting flange due to the wind loads or overpressure environment during a Shuttle launch. The wind load varies and comes from any direction causing a fatigue loading condition in the mounting flange and outer dewar shell. A structural analysis of the dewar shell showed that minor structural beef-up is required to spread the load and assure adequate design margins required by the ASME codes.

Wind - 125 MPH Max.

Drag Force = 2123 Lb.

Launch Environment - 2 PSIG Overpressure

Drag Force = 5443 Lb.



Weight

Cold Box Shell	2,401 Lb.
High-Temp. GN_2 and LN_2 Heat Exchangers	836
High-Temp. H_2 Heat Exchanger	500
Low-Temp. Heat Exchanger	568
Condenser	409
Hydrogen Purifier	400
Valves, Plumbing and Supports	266
Total:	5,380 Lb.

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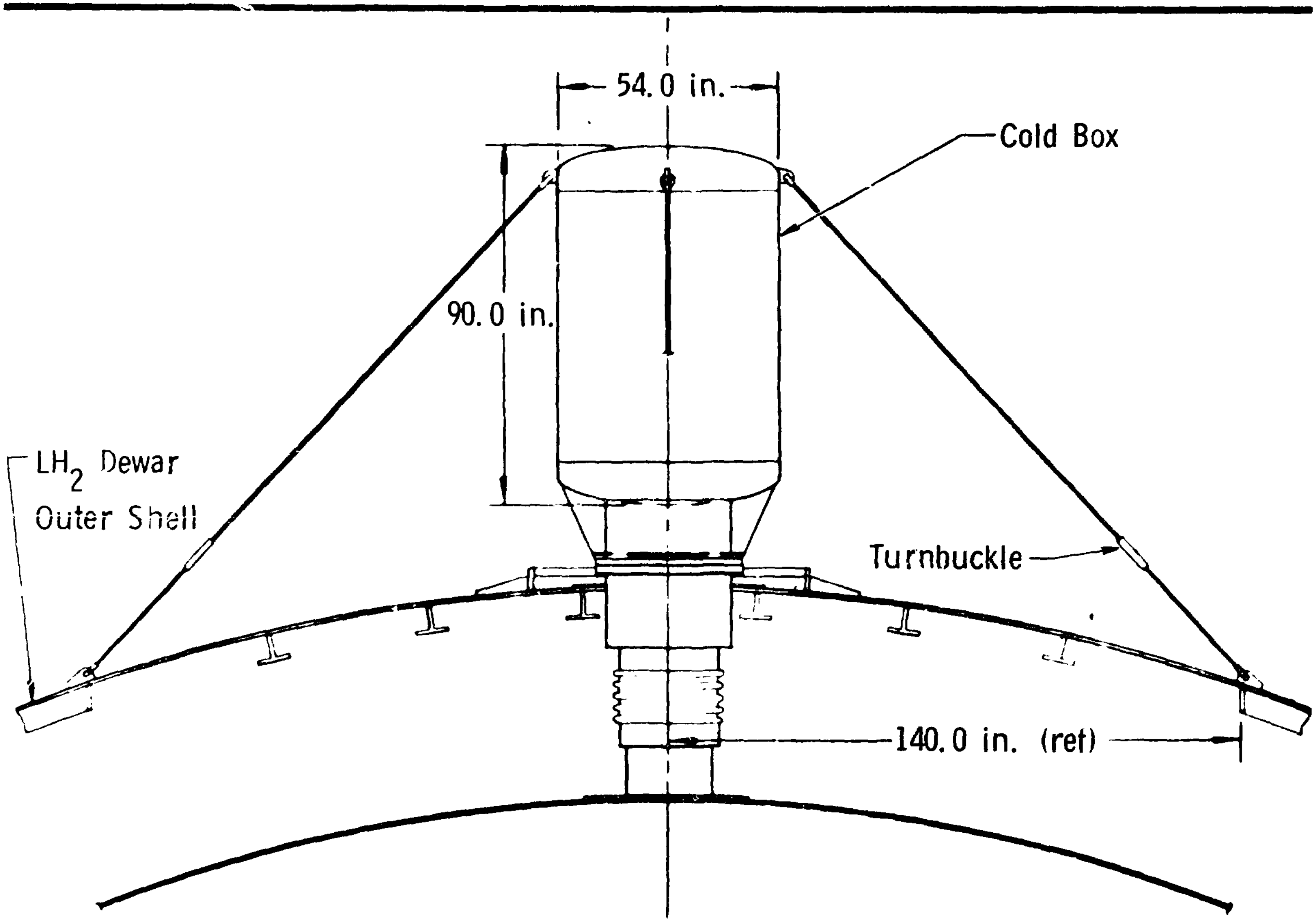
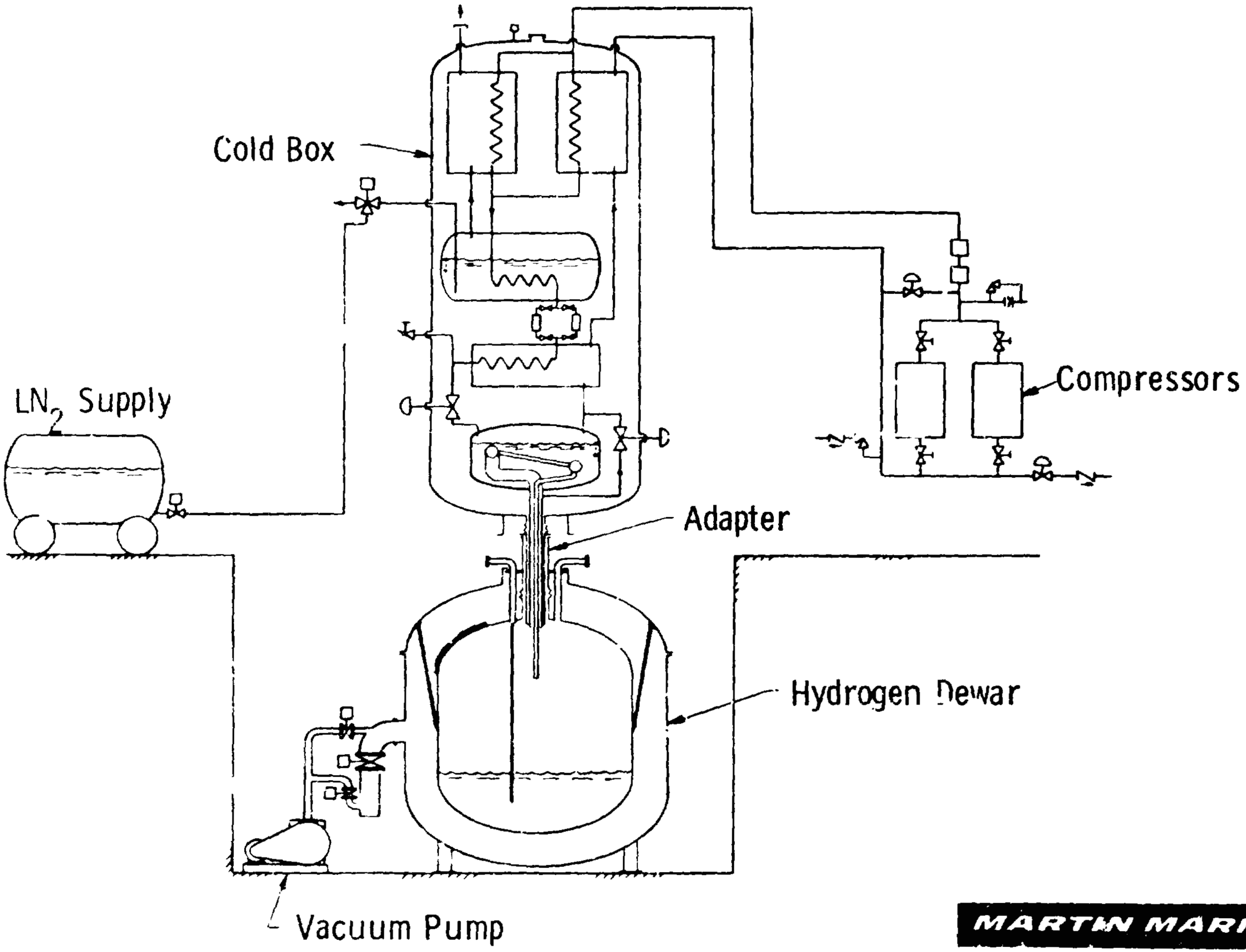
The cold box installation details are as illustrated. The dewar structural modification consists of stiffening gusset plates that extend radially from the manhole penetration and pre-tensioned guy wires or support rods to eliminate fatigue loading into the manhole flange. These modifications will incorporate all design margins imposed by the ASME codes.


54.0 in.
Cold Box
90.0 in.
LH2 Dewar
Outer Shell
Turnbuckle
140.0 in. (ref)

Verification of the LH_2 reliquefaction system operational parameters prior to installation at KSC is essential. This may be accomplished by assembling the system, mounting the cold box to a facility hydrogen dewar and operating the system over its range of operating conditions. Performance can be measured by comparing boiloff rates under known heat load conditions without the liquefier system and with the liquefier system. Much of the test facility required to perform this type testing exists at the Engineering Propulsion Laboratory of Martin Marietta Corporation, Denver Division.

PERFORMANCE TEST SCHEMATIC



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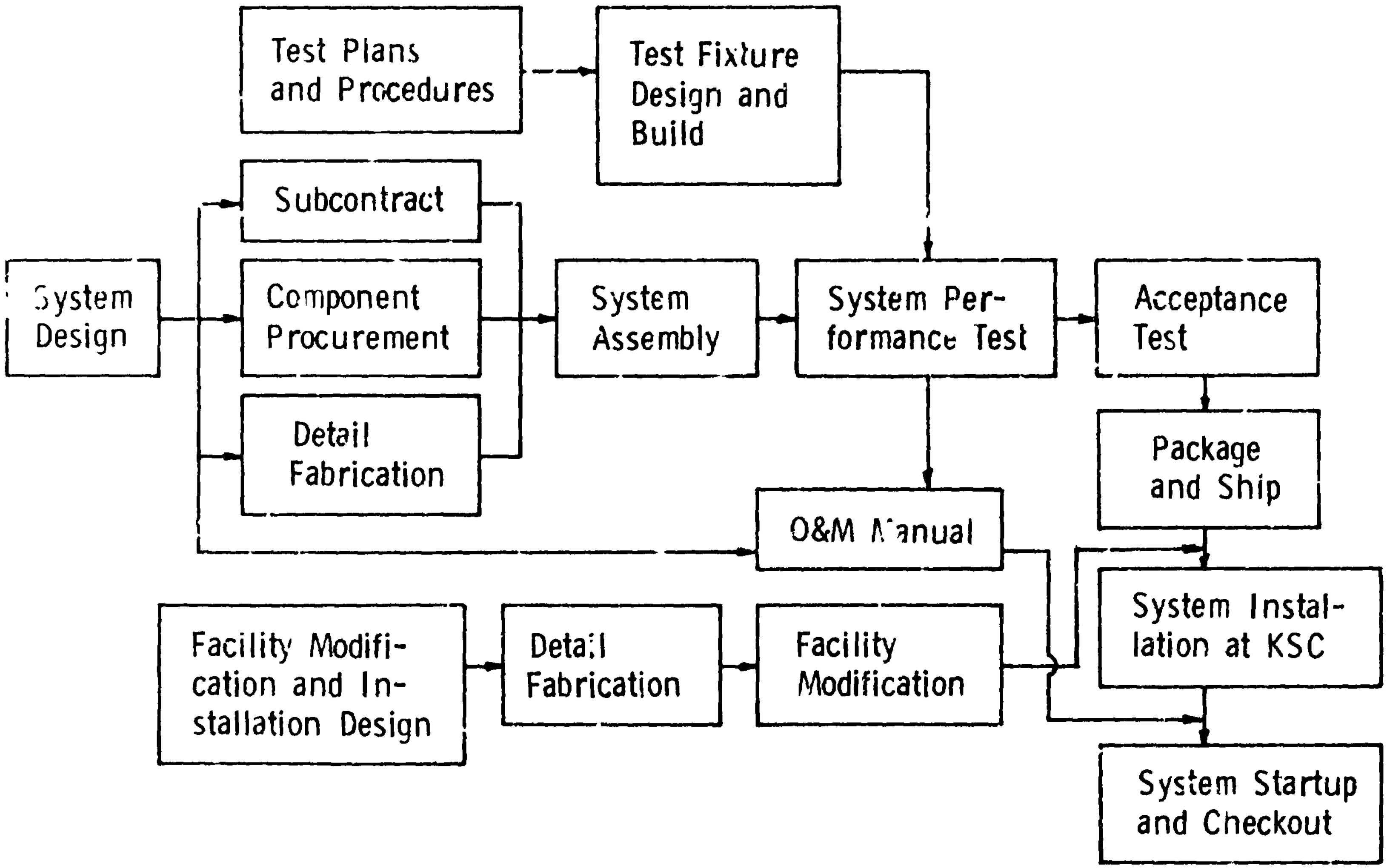
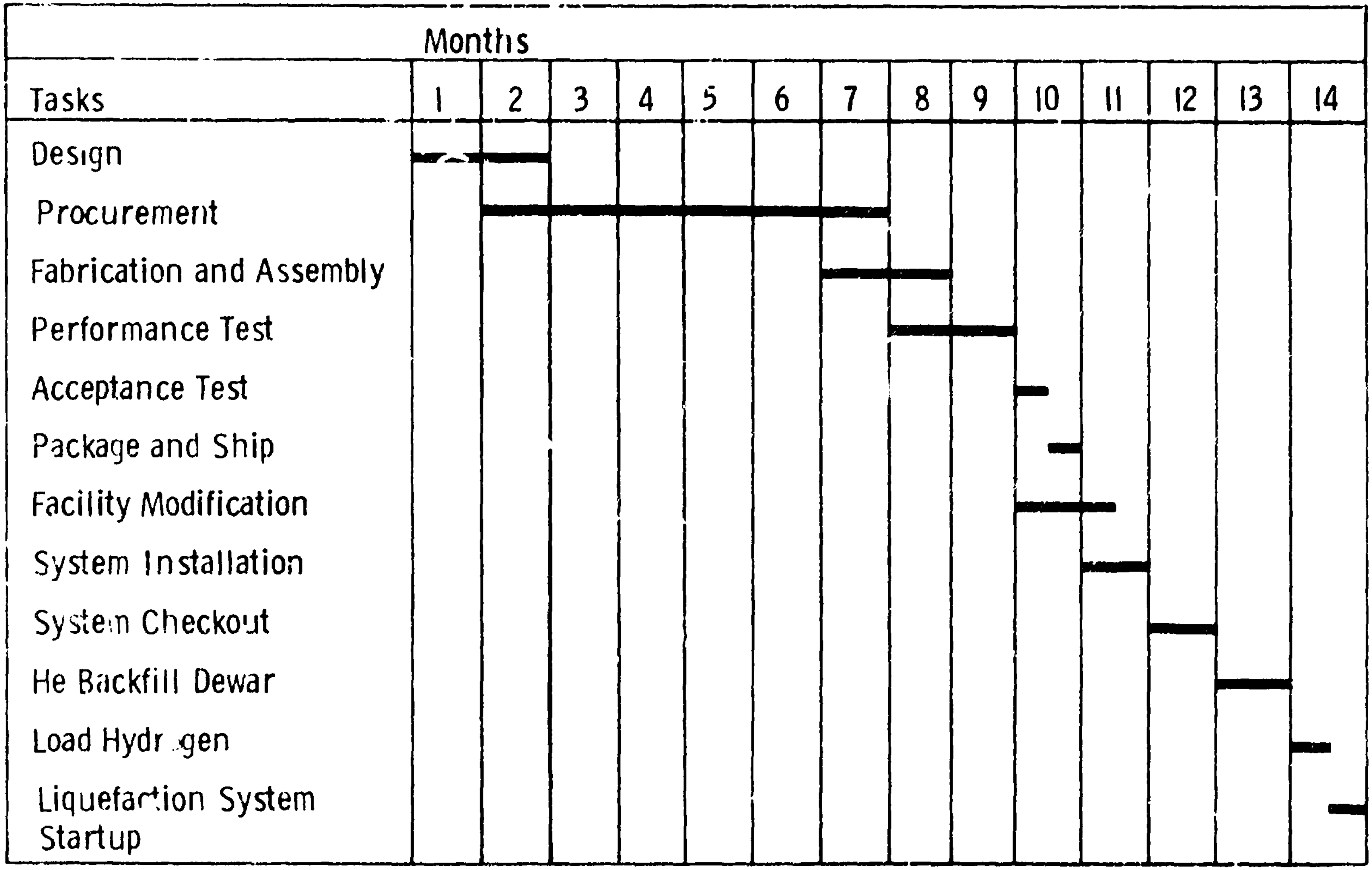
This flow diagram depicts the major tasks to implement the LH_2 reliquefaction system at Launch Complex 39B, Kennedy Space Center.

IMPLEMENTATION TASKS



The LH_2 reliquefaction system can be operational at LC-39B at KSC in a period of 14 months after authorization to proceed. The essential preliminary design and analyses have been completed. Key to the schedule is the procurement lead times required for the build of the compressors and the cold box. Written cost and schedule estimates have been provided for these items from reputable, qualified suppliers. The schedule includes two months of system performance testing prior to delivery at KSC, one month of checkout after installation, and two weeks of startup operations.

IMPLEMENTATION SCHEDULE



A statement of work defining the nine major tasks to implement the LH_2 reliquefaction system at LC-39B has been developed. The labor and equipment costs associated with each task are as shown, resulting in a total capital investment of $607,000.

The costs are based on labor and burden rates in existence at the Martin Marietta Denver Division for January 1978. Material and component costs are based on written and telecon quotations from qualified suppliers.

Task 1	Design	$ 43,000
Task 2	Raw Materials and Subcontract	334,000
Task 3	Fabrication and Assembly	28,000
Task 4	Performance Test	39,000
Task 5	Acceptance Test	8,000
Task 6	Pack and Ship (Labor, Material & Transportation)	8,000
Task 7	Facility Modification and Installation	112,000
Task 8	Start-up and Checkout	25,000
Task 9	Documentation and Reporting	10,000
		$607,000

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The results of the life cycle cost analysis based on eight launches per year and a twelve-hour dewar recovery time are shown by the printout. Note that the capital investment used was $575,000 (an earlier estimate). This was not upgraded to the current estimate of $607,000 because sensitivity analyses show that capital investment has very little effect on overall net cost savings for the program (see page 19).

The assumed maintenance, operating cost, escalation rates and operational parameters used in the program are given. The analysis shows that payback occurs in year 3 with a net savings of about $2,000,000.

Note that the cost of liquid hydrogen ($1.75/pound) was not escalated which results in considerable conservatism.

ECONOMICS - EIGHT LAUNCHES/YEAR

CAPITAL INVESTMENT COST
- EQUIP AND MATL= $ 295985.00
- DETAILED DESIGN=$ 69929.00
- FABRICATION =$ 74255.00
- INSTALLATION =$ 134831.00
- TOTAL = (1.00) $ 575000.00

OPERATING COST
- LABOR TIME= 8.0 HR/WEEK
- LABOR RATE= 12.00 $/HR
- POWER RATE= .024 $/KW-HR
- LN2 RATE = .041 $/LB
- WATER RATE= .0003 $/GAL

MAINTENANCE COST DATA
- LABOR TIME= 6.9 HR/WEEK
- LABOR RATE= 12.00 $/HR
- MATERIALS = 500.00 $/YEAR

SAVINGS DATA
- HYDROGEN RELIQUEFIED
  - NORMAL BOILOFF = 400.0 GAL/DAY
  - SHUTTLE LAUNCH = 530.5 GAL/LOADING
  - DEWAR LOADING = 8848.0 GAL/LOADING
  - TOTAL = 129158.7 LB/YEAR
- LIQ HYDROGEN COST= 1.75 $/LB

ESCALATION RATES,PERCENT/YEAR
- OPERATING LABOR= 6.00
- MAINTEN. LABOR = 6.00
- MAINTEN. MATL = 6.00
- POWER = 10.00
- LIQ NITROGEN = 10.00
- WATER = 6.00
- LIQ. HYDROGEN = 0.

OPERATIONAL PARAMETERS
- PERCENT DOWN TIME = 1.0%
- NO. OF SHUTTLE LAUNCHES/YEAR= 8.0
- NO. OF DEWAR LOADINGS/YR = 8.0

------------------------ CASH FLOW ------------------------

TOTAL CAPITAL INVESTMENT COST = $ 575000.00

YEAR	OPERATING COST	MAINTENANCE COST	TOTAL COST	GROSS SAVINGS	NET SAVINGS
1	$ 23652.2	$ 4805.6	$ 603457.8	$ 226027.7	$ -377430.1
2	$ 25809.2	$ 5093.9	$ 30903.1	$ 226027.7	$ 195124.6
3	$ 28169.3	$ 5399.6	$ 33568.9	$ 226027.7	$ 192458.8
4	$ 30752.2	$ 5723.5	$ 36475.7	$ 226027.7	$ 189552.0
5	$ 33579.3	$ 6067.0	$ 39646.3	$ 226027.7	$ 186381.4
6	$ 36674.3	$ 6431.0	$ 43105.2	$ 226027.7	$ 182922.5
7	$ 40062.9	$ 6816.8	$ 46879.8	$ 226027.7	$ 179147.9
8	$ 43773.8	$ 7225.8	$ 50999.6	$ 226027.7	$ 175028.1
9	$ 47837.9	$ 7659.4	$ 55497.3	$ 226027.7	$ 170530.4
10	$ 52289.7	$ 8119.0	$ 60408.7	$ 226027.7	$ 165619.0
11	$ 57166.8	$ 8606.1	$ 65772.9	$ 226027.7	$ 160254.8
12	$ 62510.5	$ 9122.5	$ 71632.9	$ 226027.7	$ 154394.8
13	$ 68366.1	$ 9669.8	$ 78035.9	$ 226027.7	$ 147991.8
14	$ 74783.6	$ 10250.0	$ 85033.6	$ 226027.7	$ 140994.1
15	$ 81817.6	$ 10865.0	$ 92682.6	$ 226027.7	$ 133345.0
	$ 707245.3	$ 111855.0	$ 1334100.3	$ 3390415.4	$ 1996315.1

PAY BACK OCCURS DURING YEAR 3

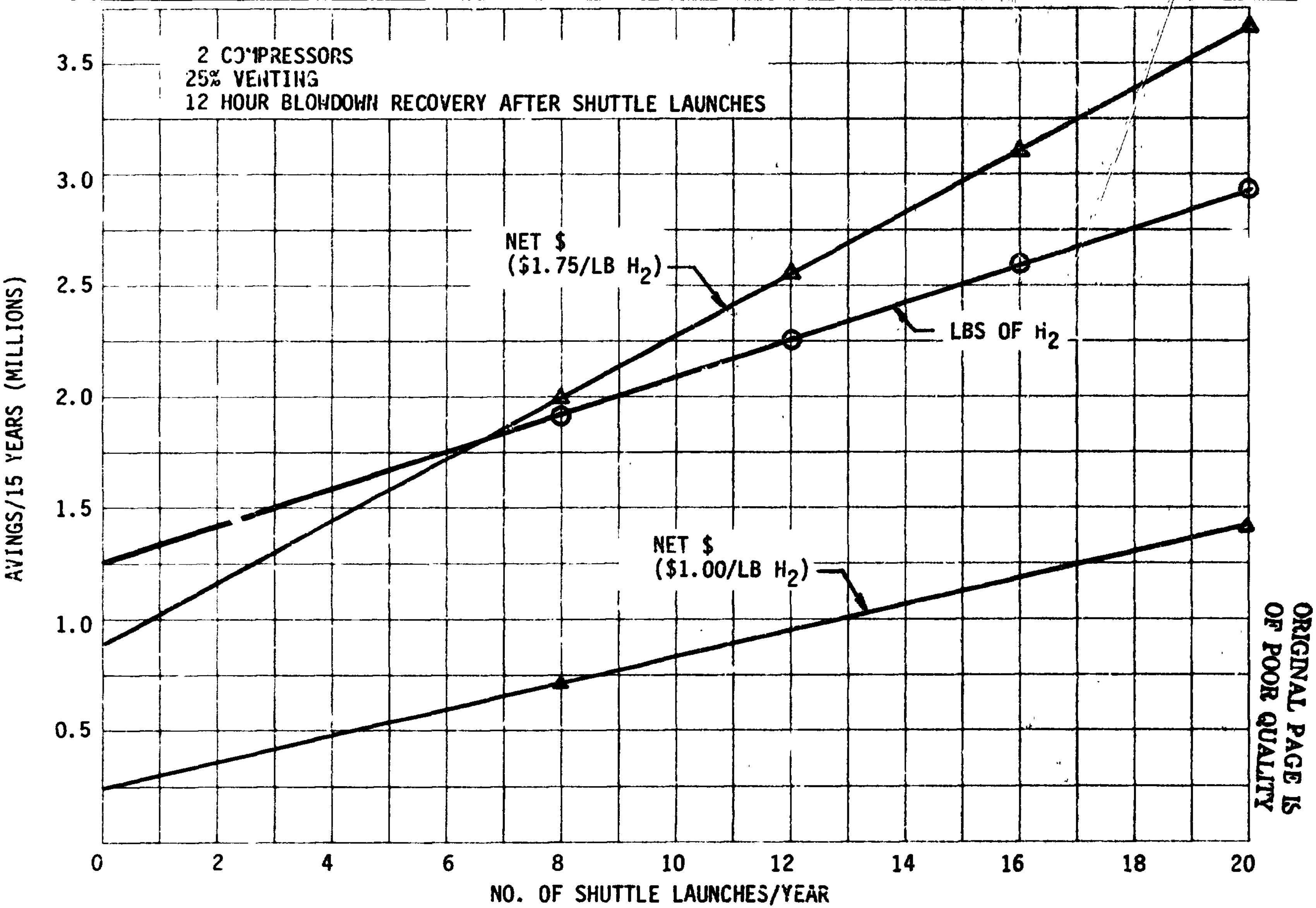
NET SAVINGS OVER 15 YEARS = 1.996 MILLION DOLLARS

------------- IN 15 YEARS -------------

TOTAL H2 SAVED WITH SYSTEM	= 1.937 MILLION LBS
TOTAL H2 LOST WITH NO SYSTEM	= 3.358 MILLION LBS
TOTAL H2 VENTED BY SYSTEM	= .418 MILLION LBS
TOTAL NITROGEN EXPENDED	= 2.539 MILLION LBS
TOTAL WATER EXPENDED	= 10.770 MILLION GALS
TOTAL POWER EXPENDED	= 7.190 MILLION KW-HR

The effect of additional Space Shuttle launches, up to 20/year is shown in terms of pounds of hydrogen saved and dollars saved for the duration of the 15-year Space Shuttle Program. Also shown is the net savings if the cost of LH_2 were only \$1/pound.

LAUNCH RATE EFFECT ON ECONOMICS



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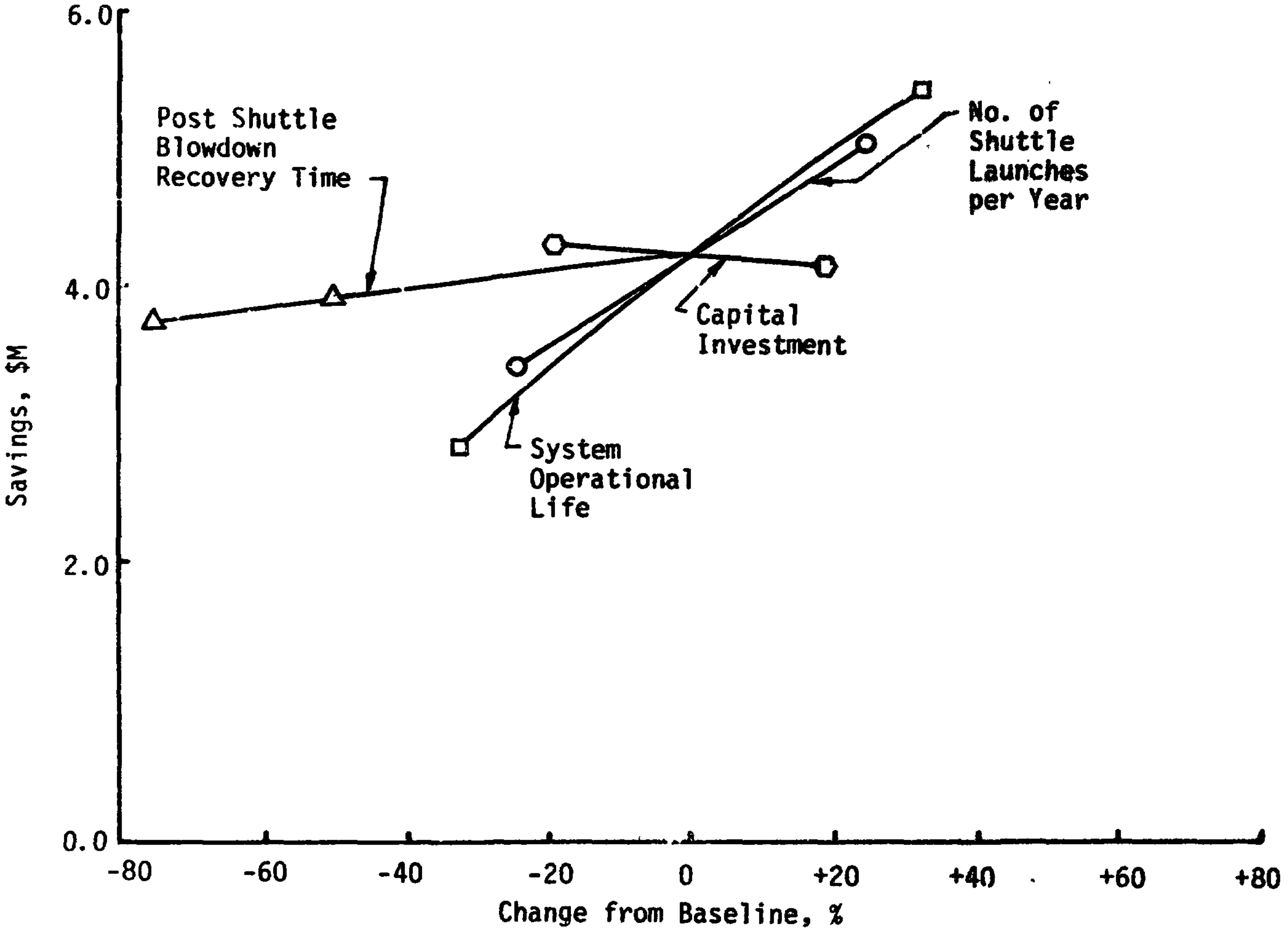
The influence of the cost study parameters (excluding hydrogen costs) on the overall net savings is as illustrated. Note that number of Shuttle launches per year and system operational life are the most influencing. Capital investment costs of $\pm$ 20% change from baseline has a very minor effect on overall savings.

INFLUENCE OF STUDY PARAMETERS ON COSTS SAVINGS



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Hydrogen reliquefaction of the boiloff from the dewars at LC-39 is technically feasible and economically attractive. All combinations of system sizes, operational conditions, and cost escalation rates that were analyzed show substantial savings with relatively short pay-back periods. The maximum savings correspond to the largest size system. The cost estimates are based on performance data generated by the system analytical model. Features of this model include coupled heat transfer and fluid flow, a detailed submodel of the low-temperature heat exchanger, and real gas properties subroutines. The predicted yields, power requirements, and LN_2 requirements, therefore, should be close to actual values.

There are no technical or safety considerations precluding the incorporation of a hydrogen reliquefaction system. The Dewar structure has been analzyed and shown to be capable of supporting the required equipment with only minor modification. A plan has been developed for penetrating the Dewar that has essentially no thermal losses. The penetration can be made without degrading the Dewar in any way. A conceptual control system has been developed that will inactivate the reliquefaction system in the event of equipment malfunction. Thus, the incorporation of a hydrogen reliquefaction system should in no way jeopardize the structural or operational integrity of the dewar.

An implementation plan has been developed that identifies the major tasks required to incorporate the hydrogen reliquefaction system on LC-39B. Detailed equipment lists were made and equipment costs quotations were obtained from reputable suppliers. Total capital investment is estimated at $607,000, based on January 1978 rates. The system can be designed, tested, installed and checked out in a period of 14 months.

A side benefit resulting from the incorporation of the LH_2 reliquefaction system is energy savings. The energy required to produce a pound of LH_2 is 7.6 KW-H versus 2.3 KW-h/pound to reclaim. Thus, approximately 2.9 million KW-H could be saved assuming eight Shuttle launches per year.

H_2 Reliquefaction is Technically Feasible

- Uses Current State-of-the Art Hardware
- No New Technology Development Required
- Analysis and Conceptual Design are Nearly Completed

Economics are Attractive

- $607,000 Initial Investment
- Payback in 2 to 3 Years Depending upon Shuttle Launch Rate
- $2M to $4M Saved Over 15 Year Program

Energy Savings are an Attractive Side Benefit

- 7.6 KW/lb. to Produce H_2 vs 2.3 KW/lb. to Reclaim

System is Safe

System Can be Operational in 14 Months

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